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BRIGHAM YOUNG UNIVERSITY  
DEPARTMENT OF CHEMICAL ENGINEERING

EXTINCTION OF BURNING SOLID PROPELLANT

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Brigham Young University  
Department of Chemical Engineering

Final Report  
Extinction of Burning Solid Propellant

Grant AF-AFOSR-897-65

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Report Prepared By:

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## INTRODUCTION

At the beginning of this program, an evaluation of the literature in the solid propellant extinction field showed that there was a considerable amount of good experimental data available (1,2,3). Although some theoretical work had also been done (4), it was felt that the initial efforts would be most profitably directed toward improving the status of the theory. Accordingly the program was set up to first, develop an improved theoretical model; second to compare the model with existing experimental data; third, to gether any additional experimental data necessary and fourth, to expand either the experimental or theoretical program as the results indicated.

## THEORY

The theoretical effort was based on the premise that the results ought to be useful to the design engineer and to be useful, the theory must not be too complex or sophisticated. At least, this seems to be true in the closely related field of combustion instability where a sizeable output of complex theory has had practically no impact on the design field. Therefore, a simple thermal model was chosen to represent the combustion process. This thermal model was indicated first because the Von Elbe treatment agreed with experiment in many cases and second, because the characteristic heat up time of the solid propellant seemed to be the only characteristic time of the combustion process which had the same magnitude as the extinction time for the propellant.

Accordingly, the combustion process was pictures as follows. The homogeneous, one-dimensional solid propellant with constant thermal properties is heated to a critical pressure-independent surface temperature where it sublimates and then reacts in the gaseous phase. The gas phase processes are comparatively rapid and for pressure transients just fast enough to

extinguish the combustion, the gas behavior is dependent only on the instantaneous pressure. Extinction occurs when the transient pressure causes the propellant surface temperature to drop below the critical value.

Appendix 1, which is a copy of a paper presented at the June, 1967 ICRPG/AIAA Solid Propulsion Symposium in Anaheim, California, presents a detailed development of the theory. This appendix also presents the theoretical results in some detail.

Where possible, the theoretical predictions were compared with the experimental data available in the literature. Qualitative agreement was realized from a qualitative comparison. However, quantitative comparison could not be made because the data in the literature were not presented in sufficient detail.

## EXPERIMENT

To remedy this deficiency, the requisite extinction data were gathered experimentally. The combustion chamber was patterned after that of Ciepluch (1) and the method of initiating the pressure transient was patterned after that used at the University of Utah (5). Thus the propellant would be ignited in a small rocket motor, the motor would reach design pressure, and then a pressure transient would be induced by rupturing a frangible diaphragm which sealed an auxiliary nozzle.

Both the experimental procedure and results are described in greater detail in Appendix 1 and Table 1 which present the results obtained from the testing of seven propellant variations. For the sake of simplicity, the table is based on the approximation that the pressure transients are exponential.

## COMPARISON OF THEORY AND EXPERIMENT

As can be seen from Table 1, the theory developed in this program agrees with experiment better than the earlier work. This improvement is accompanied

however, by increased difficulty of application. Also, even with this improvement, the theory is not yet adequate for design purposes. No comparison was made between this theory and the more sophisticated theories now in existence because the more sophisticated theories cannot yet be quantitatively related to the experimental data.

#### ACKNOWLEDGEMENT

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TABLE I

## Comparison of Theory and Experiment

| <u>Propellant*</u> | <u>Initial<br/>pressure<br/>(psia)</u> | <u>Experimental<br/>half time**<br/>(sec)</u> | <u>Reference 4<br/>Theoretical half time<br/>(sec)</u> | <u>This Theory<br/>half time<br/>(sec)</u> |
|--------------------|----------------------------------------|-----------------------------------------------|--------------------------------------------------------|--------------------------------------------|
| A-13               | 165                                    | .0100-.0107                                   | .0040                                                  | .010-.0107                                 |
| A-13               | 410                                    | .006-.009                                     | .0016                                                  | .006-.009                                  |
| A-13               | 90                                     | .0105-.012                                    | .0074                                                  | .0105-.012                                 |
| A-14               | 280                                    | .0056-.0085                                   | .00064                                                 | .0028-.0043                                |
| A-14               | 155                                    | .0057-.0085                                   | .0017                                                  | .0043-.0058                                |
| A-16               | 320                                    | .0016-.0022                                   | .00019                                                 | .0008-.0011                                |
| A-15               | 285                                    | .0053-.0075                                   | .00093                                                 | .001-.0015                                 |
| A-17               | 170                                    | .0067-.0079                                   | .046                                                   | .035-.04                                   |
| A-18               | 155                                    | .0062-.0070                                   | .028                                                   | .031-.035                                  |
| G                  | 125                                    | .0068-.0085                                   | .0035                                                  | .0023-.0041                                |

\* See appendix 1 for compositions

\*\* All of these runs were made to a final pressure of 12.5 psia. The interval represents the area separating a non-extinguishing run from one which extinguished.

## APPENDIX 1

### DEPRESSURIZATION INDUCED EXTINCTION BY BURNING SOLID PROPELLANT<sup>1</sup>

by

M.D. Horton<sup>2</sup>, P.S. Bruno<sup>3</sup>, E.C. Graesser<sup>4</sup>

#### ABSTRACT

This paper presents the results of a combined theoretical and experimental study of the process in which solid propellant combustion is terminated by a rapid drop in pressure. Experimentally, propellant burning in a small rocket motor was subjected to a rapid pressure drop when an auxiliary nozzle was suddenly opened. Such tests were run with varying nozzle sizes for the auxiliary nozzle and the boundary between extinction and non-extinction was determined. The results were then compared to the predictions of the theoretical model which was based on the assumption that extinction occurs when the heat absorption by the solid propellant exceeds the heat transfer to the solid propellant from the combustion gas. In general, the theoretical predictions agreed well with both the experimental results gathered in this program and those published by other investigators.

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## INTRODUCTION

Many solid propellant applications are dependent upon the designer's ability to cause a termination of the propellant combustion. For example, a stop-start capability may be desired for space missions, and a termination is programmed for the last stage of a ballistic missile. Because of these needs, engineers have developed and used non-optimal termination techniques. Subsequent work in the area has been directed toward understanding extinction and improving this portion of a rocket's performance.

The experimental study of propellant extinguishment by pressure decreases has been performed largely in two types of apparatus. In one, the rarification tube, a pressure transient is produced by bursting a diaphragm at the end of a tube which contains a burning strand of propellant. The resultant pressure wave then impinges upon the propellant whose response to the transient is observed. The other technique involves firing a small motor, allowing it to reach operating pressure, and then stepwise increasing the nozzle area to cause a pressure transient.

Price<sup>(1)</sup> and McCune<sup>(2)</sup> reported early exploratory tests performed with rarification tubes. However, Mitchell<sup>(3)</sup> later showed that such extinction as was previously observed had probably been caused by the flow of cold, inert gas around the propellant strand. Donaldson<sup>(4)</sup> later performed an extensive series of rarification tube tests and obtained good qualitative results.

Ciepluch<sup>(5,6,7)</sup> studied the extinction of several propellants by the use of a small motor having an auxiliary nozzle which opened after steady state combustion was attained. The reports of his work describe the effect of propellant composition on reignition, and also the depressurization rate required to produce extinction. Reference 8 also describes results of this nature.

The theoretical studies performed thus far have been only partly successful. References 8 and 9 develop the transient burning rate equation:

$$\frac{r}{r_0} = 1 + \frac{\alpha n N}{b^2 P^{2n+1}} \frac{dP}{dt} \quad (1)$$

which says extinction occurs ( $r = 0$ ) when

$$\frac{-dP}{dt} = \frac{b^2 P^{2n+1}}{N \alpha n} \quad (2)$$

According to Reference 8,  $N$  has a value of one or less, while Reference 9 says  $N$  has a value of 2.

Equation 2 provides a qualitative correlation of the experimental data, but a better theoretical description is required for two reasons. One reason is that, as Figure 1 show, the correlation is not adequate for general engineering use. Another reason is that Equation 2 does not consider the effect of total pressure drop which experiment<sup>(7)</sup> has shown to be important.

The object of this paper is to present the results of a study in which an improved theoretical model explaining extinction was developed. Also presented are experimental extinction data for propellant compositions not previously tested.

#### EXTINCTION MODEL

To derive a rigorous theory describing extinction, one would develop the time dependent heat conduction, diffusion, and kinetic equations for both the gas and solid phases of the combustion zone, and then solve them simultaneously. Besides being extremely difficult, this task would, upon completion, yield a very complex solution. In fact, the solution would be so complex and contain so many parameters whose values were unknown that such a solution would have little practical value.

The task could, perhaps, be simplified by the use of perturbational analysis, except that here again difficulties intervene. During the pressure transient being considered, many pertinent variables change by a factor of ten or greater. This being so, one must be concerned not with a perturbation of the initial conditions, but rather with the entire transient of interest.

Fortunately, the problem can be somewhat simplified if consideration is given to the various characteristic times for the combustion process. Reference 10 has shown that the characteristic times for the gaseous portion of the combustion zone are considerably smaller than the characteristic time associated with heat conduction in the solid propellant. Accordingly, the heat-up of the solid propellant is the slowest in the series of events that transforms the solid propellant into a hot combustion gas. Because the heating of the solid is the rate limiting (i.e. slowest) step, the minimum pressure transient which will terminate combustion is the one which is just fast enough to arrest this rate-limiting step.

In order to derive a thermal extinction criterion, it is first convenient to describe the steady state thermal profile in the solid propellant. The heat conduction equation in the solid propellant is:

$$\alpha \frac{\partial^2 T}{\partial x^2} - r_i \frac{\partial T}{\partial x} = \frac{\partial T}{\partial t} \quad (3)$$

if it is assumed that:

- (1) the heat conduction is one-dimensional
- (2) there are no reactions beneath the propellant surface
- (3) the thermal properties of the propellant are constant
- (4) the propellant is homogenous and semi-infinite, and
- (5) the coordinate system is fixed with respect to the propellant surface

At steady state  $\frac{\partial T}{\partial t} = 0$  and the temperature distribution in the solid propellant is (see Figure 2):

$$\frac{T - T_o}{T_s - T_o} = \exp\left(-\frac{\Gamma x}{\alpha}\right) \quad (4)$$

Now, it is further assumed that the propellant sublimates with a pressure-independent heat of sublimation when it is heated to a certain critical, pressure-independent temperature ( $T_s$ ). Certainly, this is not an exact description of the surface decomposition, but it may be an adequate representation as will be determined by a comparison of the theoretical predictions and experimental data.

The consequence of these assumptions is that any time the surface temperature drops below  $T_s$ , extinction has occurred. Furthermore, the only way the surface temperature can drop is for the heat conduction into the propellant to be greater than the heat conduction from the gaseous flame to the propellant surface.

The heat conduction into the solid is  $k \frac{\partial T}{\partial x} \big|_{x=0}$ , whereas it is more difficult to describe the conduction to the surface. To facilitate this description, another approximation is made. This approximation is that the rate of heat conduction from the gas flame to the solid surface is characterized only by the pressure. That is, at a given pressure, the heat transfer is the same during a pressure transient as it would be if the pressure were constant. To some degree, the approximation is justified because the characteristic times for the gas are small compared with the characteristic time of the solid.<sup>(10)</sup> This means that the gas flame responds rapidly enough that its behavior is not time-dependent, but only pressure dependent. Again, the ultimate justification must come from satisfactory agreement between experiment and theory. The

heat conducted into the solid from the surface is equal to that conducted to the surface minus the heat required to vaporize the solid. With the above assumptions and approximations, these respective terms are  $k \frac{\partial T}{\partial x} \Big|_{x=0}$ ,  $r \rho \lambda + r \rho c (T_s - T_o)$ , and  $r_i \rho \lambda$ . The equation which relates these terms is:

$$k \frac{\partial T}{\partial x} \Big|_{x=0} = \rho \lambda (r - r_i) + r \rho c (T_s - T_o) \quad (5)$$

At this point Equation 3 describes the heat transfer in the solid, Equation 4 is a boundary condition describing the initial temperature profile when the pressure transient is induced, and Equation 5 describes the transient heat transfer to the solid surface. Additional boundary conditions are that  $T_s$  is a constant and the temperature at minus infinity is  $T_o$ .

For the sake of generality, these equations were non-dimensionalized by the use of the following definitions, many of which were used in Reference 8:

$$\theta = \frac{T - T_o}{T_s - T_o} \quad (6)$$

$$Y = \frac{r_o x}{\alpha}$$

$$\tau = \frac{r_o^2 t}{\alpha}$$

$$R = \frac{r}{r_o}$$

$$R_i = \frac{r_i}{r_o}$$

$$F = \frac{\lambda}{c(T_s - T_o)}$$

The substitution of these dimensionless variables converted the heat-transfer equations and boundary conditions to:

$$\frac{\partial^2}{\partial Y^2} - R_i \frac{\partial \theta}{\partial Y} = \frac{\partial \theta}{\partial \tau}$$

$$\left. \frac{\partial \theta}{\partial Y} \right|_{Y=0} = (1+F) R - R_i F \quad (7)$$

$$\theta = 0 \text{ at } Y = -\infty$$

$$\theta = \exp Y \text{ at } \tau = 0$$

and

$$\theta = 1 \text{ at } Y = 0$$

Provided that the relationship between  $R$  and  $\tau$  ( $P$  and  $t$ ) were known, one could, in principle, find an exact solution to this set of equations. However, even with a simple specification of  $R$  versus  $\tau$ , the authors could not find an exact solution and resorted to numerical techniques. By the application of the backward method of differences, a tridiagonal system of difference equations was developed and then numerically solved with an IBM 7040 computer for two types of  $R$  vs.  $\tau$  relationships.

The first type was chosen because it was a fair approximation of the relationship encountered experimentally. This form was based on the assumption that the pressure decay in the combustion system was described by the exponential equation:

$$\frac{P - P_a}{P_o - P_a} = \exp \left( \frac{-0.693\tau}{\tau_{1/2}} \right) \quad (8)$$

while the steady state burning rate of the propellant could be described as:

$$r = bP^n \quad (9)$$

Then, the equation

$$R = \frac{r}{r_o} = \left( \frac{P}{P_o} \right)^n \quad (10)$$

was used along with Equations 8 and 10 to obtain

$$R = \left[ \left( 1 - \frac{P_a}{P_o} \right) \exp \left( \frac{-0.693}{\tau_{1/2}} \right) + \frac{P_a}{P_o} \right]^n \quad (11)$$

Equations 7 and 11 were then solved numerically for the critical values of  $\tau_{1/2}$  which represented the boundary condition between fast decays (small  $\tau_{1/2}$ ) which theoretically caused extinction ( $R_1 = 0$ ) and slower decays which did not. Figures 3 and 4 summarize the results.

In many cases of interest, either or both of Equations 8 and 9 did not adequately describe the transient. When this was so, Equation 11 was not used as a boundary condition but instead, the computer program used a data table of  $R$  versus  $\tau$  as prepared from the strand burning rate curve and the pressure decay record of a particular extinction test. The numerical solution would then determine whether or not the propellant should have extinguished theoretically. The results of such tests were examined by this procedure and are presented later in the paper.

#### EXTINCTION TESTS

Although much experimental extinction data were available in the literature, they did not meet the needs of this program for two reasons. First, because propellant compositions not previously tested were of interest and second, because the data as presented did not allow a comparison between experiment and theory. That is, the pressure transients in the literature were non-exponential, so Equation 11 was not a valid boundary condition. Also, the experimental decays were rarely presented in a sufficient detail to permit the determination and use of a tabular boundary condition. One experimenter was generous enough to furnish the authors with his detailed experimental results.<sup>(11)</sup> However, the data were originally taken for different purposes and were not detailed enough to allow a direct comparison with theory.

Therefore, the propellant compositions listed in Table I were tested to determine the conditions required to extinguish the propellant combustion. This testing was done in motors which were ignited, allowed to come to operating pressure, and then subjected to a pressure transient by instantly opening an auxiliary nozzle. The use of several different auxiliary nozzle sizes established the boundary between the transient which extinguished combustion and the transient which did not. Studied in the program were the effect of propellant location, propellant composition, initial pressure, and final pressure. Table 2 presents a summary of the test results.

As Reference 6 has shown, small changes in composition can cause large changes in the extinguishment characteristics of a propellant. Other variables had less effect but were still significant.

#### DETERMINATION OF F

The reader may have noticed that all but one of the parameters used in the theory can be readily determined from routine laboratory tests. Recent work <sup>(12)</sup> has also made it possible to determine the value of F. Briefly, the value of F is determined as follows. A rarification tube is used to determine the total pressure drop required to extinguish a burning propellant strand as a function of depressurization rate. This curve is then extrapolated beyond the experimental limit to find the required pressure drop ( $P_0$  to  $P_f$ ) for an instantaneous drop in pressure. This parameter is then related to F by noting that, according to the assumptions made earlier, an instantaneous pressure drop will cause the heat flux from the gas phase to instantaneously readjust while the thermal profile in the solid is unchanged. The extinction condition is represented by the point where the heat conduction to the surface  $r\rho\lambda + r\rho c (T_s - T_c)$  is just equal to the conduction away from the surface  $r_0 \rho c (T_s - T_0)$  and

$$r \rho [ \lambda + c (T_x - T_o) ] = r_o \rho c (T_s - T_o) \quad (12)$$

Equation 9 is then used as

$$r = b P_f^n \quad (13)$$

and

$$r_o = b P_o^n$$

then combined with Equation 12 to give:

$$\left( \frac{P_o}{P_f} \right)^n = \left[ \frac{\lambda}{c (T_s - T_o)} + 1 \right] \quad (14)$$

which, after the substitution of F and rearrangement, becomes

$$F = \left( \frac{P_o}{P_f} \right)^n - 1 \quad (15)$$

For several of the propellants tested in the extinction program, the values of F and the parameters used in their calculation are shown in Table III.

#### COMPARISON OF THEORY AND EXPERIMENT

Even though the theoretical model could not quantitatively be compared with the experimental data available in the literature, some qualitative comparisons were made. Ciepluch (Figure 3 in Reference 6) shows a graph of the maximum "half-decay time" ( $t_{1/2}$ ), which will cause extinction as a function of initial pressure. From the definition of  $\tau$ , we find that

$$\tau_{1/2} = \frac{r_o^2}{\alpha} t_{1/2} \quad (16)$$

Now, to compare theory and experiment, the rather poor assumption was made that the experimental pressure decay is exponential. Then, for reasonable values of F (see Tables 2 and 4), Figures 3 and 4 show that  $\tau_{1/2}$  is a constant over the pressure range being considered ( $n = .34$ ,  $P_a/P_o = .001$ ). As figure 5 shows, the experimental data have about the same values as the theory

( $F = 0.1$ ), but the experimental data show a slight slope. Accordingly, the model and experimental data show qualitative agreement which is about all that could be expected in this case.

Reference 6 presents data for the critical half decay time as a function of ambient pressure for an aluminized propellant. Figure 6 shows a comparison between the theory and the experimental results and again qualitative agreement is observed.

In one case, an illustration in the literature<sup>(5)</sup> presented exact pressure-time history during an extinction test. This history was used to prepare a table of  $R$  vs.  $\tau$  for computer input. Then, with an assumed representative value of  $F = 0.10$ , the theory correctly predicted extinction. Because an exact value of  $F$  was unknown, this result represents qualitative agreement between experiment and theory.

Similarly, the  $F$  values for several of the propellants tested in this program were unknown. However, the use of an assumed value (0.14) and tabular input of the boundary condition yielded excellent agreement between the experimental results and the theoretical predictions with agreement being obtained in fourteen out of fifteen comparisons. This again constitutes good qualitative agreement.

For those propellants whose  $F$  values were known (See Table III), use of tabular input of the boundary condition provided a severe test for the theoretical model. These seven propellant compositions were tested and the theory correctly predicted extinction for 18 out of 25 tests. To determine how serious the error in the model was, the seven tests showing disagreement were further examined. Faster or slower decays were synthetically generated and used to determine the extinction-non-extinction boundary. By this process it was found that to predict extinction the model required depressurization rates

which were in error by as much as a factor of five. For example, to predict extinction for run 119, the model needed a depressurization rate at least three times as fast as the experimentally observed value.

It is appropriate that this theory be compared with that presented in References 8 and 9. The perturbational approach used in those references yields a criterion which is very simple to use and which disagreed by no more than a factor of ten with the experimental results determined in this program. However, that approach wrongly predicts no relation between extinction and ambient pressure. The model presented in this paper requires complex numerical calculation but seems to be correct within a factor of five and correctly predicts trends. It would seem then, that the older theory is not as good but is easier to use.

One factor which was examined experimentally was the effect of propellant orientation in the combustion chamber. It was found that an end burner was slightly easier (25 percent smaller depressurization rate) to extinguish than a single slab subjected to parallel flow which in turn was slightly easier (20 percent) to extinguish than opposed slabs subjected to parallel flow.

The practical implications of Figures 3 and 4 are many. According to the theory, anything that lowers the effective propellant surface temperature or raises its "heat of sublimation" will make the propellant easier to extinguish. For low values of  $P_a / P_o$ , a small increase in either chamber pressure or pressure exponent can make a motor much easier to extinguish. Also, under any conditions, very low exponent propellants are difficult to extinguish. Unfortunately, the experimental data required to test these predictions are not available.

As the model was used, it was necessary to know the experimental pressure decay to see if the theory would predict extinction. The theory would be

much more useful if it were coupled to a mass balance on the combustion chamber so that the computer would generate the pressure transient equation. While such a coupling was accomplished in this program, an overly simple mass balance was used and high quality results were not obtained.

## DISCUSSION

At this point, consider how good the theory could be expected to be and then how good it actually is. The theoretical model is relatively simple and unsophisticated. The solid is not homogeneous, the thermal properties are not constant, the surface temperature is not constant, subsurface reactions almost surely occur, the use of the term  $\lambda$  represents a drastic simplification of the surface decomposition, and the representation of the gas phase heat transfer may be a poor approximation. With these objections in mind, one would not expect more than qualitative agreement between theory and experiment.

Now, the comparisons made showed qualitative agreement in all cases and quantitative agreement in most cases. This is better than one would expect, considering the simplicity of the theory and the wide range of propellant compositions considered. The theory then, consists of a fairly accurate thermal representation of the extinction process. Because all of the parameters used can be determined experimentally, no "guess" factors are left as uncertainties. Accordingly, the theory and experimental method ought to be useful to anyone concerned with practical extinction problems.

## NOMENCLATURE

|           |                                                                                                      |
|-----------|------------------------------------------------------------------------------------------------------|
| A         | Exponential pressure decay exponent                                                                  |
| b         | Constant in Vielle steady state burning rate equation                                                |
| c         | Propellant heat capacity                                                                             |
| F         | Ratio of propellant heat of vaporization to heat required to raise propellant to surface temperature |
| k         | Propellant thermal conductivity                                                                      |
| n         | Pressure exponent in Vielle burning rate equation                                                    |
| N         | Coefficient in Von Elbe and Aerojet Extinction Theory                                                |
| P         | Instantaneous chamber pressure                                                                       |
| $P_a$     | Ambient pressure                                                                                     |
| $P_f$     | Final pressure in rarifaction tube                                                                   |
| $P_o$     | Initial steady state chamber pressure                                                                |
| r         | Steady state burning rate corresponding to P                                                         |
| $r_i$     | Transient burning rate                                                                               |
| $r_o$     | Steady state burning rate corresponding to $P_o$                                                     |
| R         | Dimensionless steady state burning rate $(\frac{r}{r_o})$                                            |
| $R_i$     | Dimensionless transient burning rate $(\frac{r_i}{r_o})$                                             |
| t         | Time                                                                                                 |
| $t_{1/2}$ | Largest time in which chamber pressure could decrease by 50% and still extinguish propellant         |
| T         | Temperature of propellant                                                                            |
| $T_o$     | Initial propellant temperature                                                                       |
| $T_s$     | Surface temperature of burning propellant                                                            |
| x         | Distance from propellant surface                                                                     |

|              |                                                                  |
|--------------|------------------------------------------------------------------|
| $Y$          | Dimensionless distance ( $r_0 x / \alpha$ )                      |
| $\alpha$     | Propellant thermal diffusivity                                   |
| $\lambda$    | Propellant heat of sublimation                                   |
| $\rho$       | Propellant density                                               |
| $\theta$     | Dimensionless temperature ( $\frac{T - T}{T_s - T_o}$ )          |
| $\tau$       | Dimensionless time ( $r_0^2 t / \alpha$ )                        |
| $\tau_{1/2}$ | Dimensionless half decay time ( $\frac{r_0^2 t_{1/2}}{\alpha}$ ) |

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TABLE I

PROPELLANT COMPOSITIONS

| <u>Propellant Designation</u> | <u>Type</u>                              | <u>Oxidizer</u>    | <u>Metal Fuel</u> | <u>Additive</u>          |
|-------------------------------|------------------------------------------|--------------------|-------------------|--------------------------|
| A                             | Conventional cast, modified, double-base | AP/HMX=1*          | 20% Al            | --                       |
| B                             | Slurry cast, modified, double-base       | AP/HMX=1           | 5% Al             | --                       |
| C                             | Conventional cast, modified double-base  | AP/HMX=1           | 20% Al            | --                       |
| A-13                          | Composite, 24% PBAN**                    | 76% 80μ AP         | --                | --                       |
| A-14                          | Composite, 24% PBAN                      | 76% 15μ AP         | --                | --                       |
| A-15                          | Composite, 24% PBAN                      | 76% 80μ AP         | --                | 1% copper chromite added |
| A-16                          | Composite, 24% PBAN                      | 76% 15μ AP         | --                | 1% copper chromite added |
| A-17                          | Composite, 24% PBAN                      | 76% 80μ AP         | --                | 1% LiF added             |
| A-18                          | Composite, 24% PBAN                      | 76% 15μ AP         | --                | 1% LiF added             |
| G                             | Composite, 20% PBAA***                   | 80% as received AP | --                | --                       |

\*AP is ammonium perchlorate

\*\*PBAN is polybutadiene-acrylonitrile

\*\*\*PBAA is polybutadiene-acrylic acid

TABLE II

## EXPERIMENTAL RESULTS

| Propellant | Composite | Identification | P <sub>o</sub><br>(psia) | P <sub>a</sub><br>(psia) | r <sub>o</sub><br>(in./sec) | t <sub>½</sub><br>(sec) | Experimentally<br>Extinguished | Theoretically<br>Extinguished | F Value<br>Used | α<br>in. <sup>2</sup> /sec |
|------------|-----------|----------------|--------------------------|--------------------------|-----------------------------|-------------------------|--------------------------------|-------------------------------|-----------------|----------------------------|
|            |           | Fig 2 of Ref 5 | 547                      | 0.1                      | .27                         | .0038                   | yes                            | yes                           | 0.10            | 0.00025                    |
| A          |           | JO 2**         | 330                      | 12.7                     | .361                        | .0038                   | yes                            | yes                           | 0.14            | 0.00036                    |
| A          |           | JO 2**         | 508                      | 12.7                     | .433                        | .0030                   | yes                            | yes                           | 0.14            | 0.00036                    |
| A          |           | JO 5**         | 5/2                      | 12.7                     | .434                        | .0040                   | no                             | yes                           | 0.14            | 0.00036                    |
| A          |           | JO 13**        | 193                      | 0.05                     | .291                        | .0043                   | (borderline)                   | yes                           | 0.14            | 0.00036                    |
| A          |           | JO 18**        | 486                      | 0.05                     | .424                        | .024                    | yes                            | yes                           | 0.14            | 0.00036                    |
| A          |           | JO 19**        | 366                      | 0.05                     | .378                        | .026                    | yes                            | yes                           | 0.14            | 0.00036                    |
| A          |           | JO 29**        | 159                      | 0.05                     | .268                        | .040                    | no                             | no                            | 0.14            | 0.00036                    |
| A          |           | JO 30**        | 319                      | 0.05                     | .358                        | .046                    | no                             | no                            | 0.14            | 0.00036                    |
| A          |           | FTM 428**      | 200                      | 0.00                     | .295                        | .018                    | yes                            | yes                           | 0.14            | 0.00036                    |
| A          |           | FTM 435**      | 300                      | 0.00                     | .348                        | .017                    | yes                            | yes                           | 0.14            | 0.00036                    |
| B          |           | JO 37**        | 407                      | 0.05                     | .500                        | .018                    | no                             | no                            | 0.14            | 0.00036                    |
| C          |           | JO 54**        | 442                      | 0.05                     | .41                         | .022                    | yes                            | yes                           | 0.14            | 0.00036                    |
| C          |           | JO 55**        | 420                      | 0.05                     | .40                         | .034                    | no                             | no                            | 0.14            | 0.00036                    |
| C          |           | JO 63**        | 313                      | 12.5                     | .34                         | .033                    | no                             | no                            | 0.14            | 0.00036                    |
| C          |           | JO 64**        | 297                      | 12.5                     | .144                        | .0107                   | no                             | no                            | 0.13            | 0.00023                    |
| A-13       |           | 10*            | 165                      | 12.5                     | .144                        | .0107                   | no                             | no                            | 0.13            | 0.00023                    |
| A-13       |           | 15*            | 164                      | 12.5                     | .143                        | .0100                   | yes                            | yes                           | 0.13            | 0.00023                    |
| A-13       |           | 16*            | 167                      | 12.5                     | .145                        | .011                    | no                             | no                            | 0.13            | 0.00023                    |
| A-13       |           | 18*            | 383                      | 12.5                     | .222                        | .0091                   | no                             | no                            | 0.13            | 0.00023                    |

TABLE II (CONT.)

## EXPERIMENTAL RESULTS

| Propellant | Identification | P <sub>o</sub> (psia) | P <sub>a</sub> (psia) | r <sub>o</sub> (in./sec) | t <sub>½</sub> (sec) | Experimentally Extinguished | Theoretically Extinguished | F Value Used | $\alpha$ in. <sup>2</sup> /sec |
|------------|----------------|-----------------------|-----------------------|--------------------------|----------------------|-----------------------------|----------------------------|--------------|--------------------------------|
| A-13       | 20*            | 440                   | 12.5                  | .237                     | .0061                | yes                         | yes                        | 0.13         | 0.00023                        |
| A-13       | 21*            | 292                   | 12.5                  | .193                     | .012                 | no                          | no                         | 0.13         | 0.00023                        |
| A-13       | 22*            | 93                    | 12.5                  | .107                     | .0105                | yes                         | yes                        | 0.13         | 0.00023                        |
| A-13       | 24*            | 89                    | 12.5                  | .104                     | .012                 | no                          | no                         | 0.13         | 0.00023                        |
| A-14       | 34*            | 158                   | 12.5                  | .248                     | .0057                | yes                         | yes                        | 0.17         | 0.00023                        |
| A-14       | 35*            | 148                   | 12.5                  | .238                     | .0085                | no                          | no                         | 0.17         | 0.00023                        |
| A-14       | 39*            | 305                   | 12.5                  | .41                      | .0056                | yes                         | yes                        | 0.17         | 0.00023                        |
| A-14       | 40*            | 260                   | 12.5                  | .37                      | .0085                | no                          | yes                        | 0.17         | 0.00023                        |
| A-16       | 44*            | 319                   | 12.5                  | .665                     | .0016                | yes                         | no                         | 0.57         | 0.00023                        |
| A-16       | 46*            | 320                   | 12.5                  | .665                     | .0022                | no                          | no                         | 0.57         | 0.00023                        |
| A-15       | 55*            | 275                   | 12.5                  | .30                      | .0053                | yes                         | no                         | 0.40         | 0.00023                        |
| A-15       | 56*            | 294                   | 12.5                  | .312                     | .0075                | no                          | no                         | 0.11         | 0.00023                        |
| A-17       | 60*            | 166                   | 12.5                  | .120                     | .0079                | no                          | yes                        | 0.11         | 0.00023                        |
| A-17       | 61*            | 174                   | 12.5                  | .122                     | .0067                | yes                         | yes                        | 0.11         | 0.00023                        |
| A-18       | 66*            | 144                   | 12.5                  | .174                     | .0062                | yes                         | yes                        | 0.11         | 0.00023                        |
| A-18       | 67*            | 170                   | 12.5                  | .188                     | .0070                | no                          | yes                        | 0.11         | 0.00023                        |
| A-13       | 68*            | 245                   | 12.5                  | .175                     | .0061                | yes                         | yes                        | 0.13         | 0.00023                        |
| A-13       | 70*            | 220                   | 12.5                  | .165                     | .0071                | yes                         | yes                        | 0.13         | 0.00023                        |
| A-13       | 71*            | 268                   | 12.5                  | .182                     | .010                 | no                          | no                         | 0.13         | 0.00023                        |
| G          | 119*           | 120                   | 12.5                  | .170                     | .0068                | yes                         | no                         | 0.17         | 0.00027                        |
| G          | 129*           | 136                   | 12.5                  | .183                     | .0085                | no                          | no                         | 0.17         | 0.00027                        |

\*end burner

\*\*opposed slabs

TABLE III  
RARIFACTION TUBE RESULTS

| <u>Propellant</u> | <u><math>P_o/P_f</math></u> | <u>n</u> | <u>F</u> |
|-------------------|-----------------------------|----------|----------|
| A-13              | 1.265                       | 0.51     | 0.13     |
| A-14              | 1.29                        | 0.61     | 0.17     |
| A-15              | 1.87                        | 0.53     | 0.40     |
| A-16              | 2.24                        | 0.56     | 0.57     |
| A-17              | 1.29                        | 0.42     | 0.11     |
| A-18              | 1.204                       | 0.57     | 0.11     |
| G                 | 1.306                       | 0.58     | 0.17     |

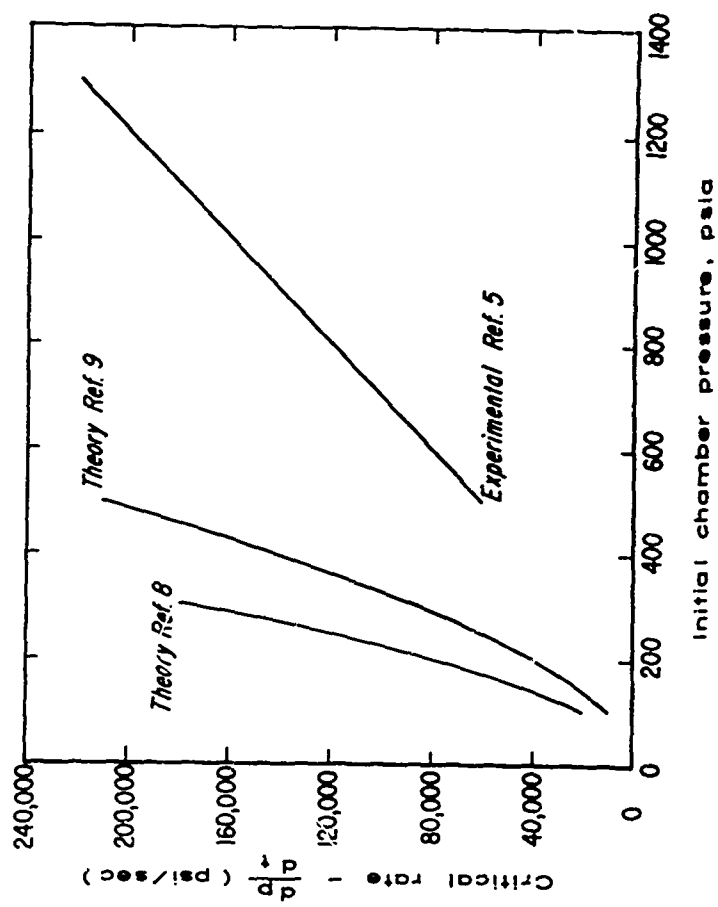


Figure 1. COMPARISON BETWEEN THEORY AND EXPERIMENTAL EXTINCTION CRITERION

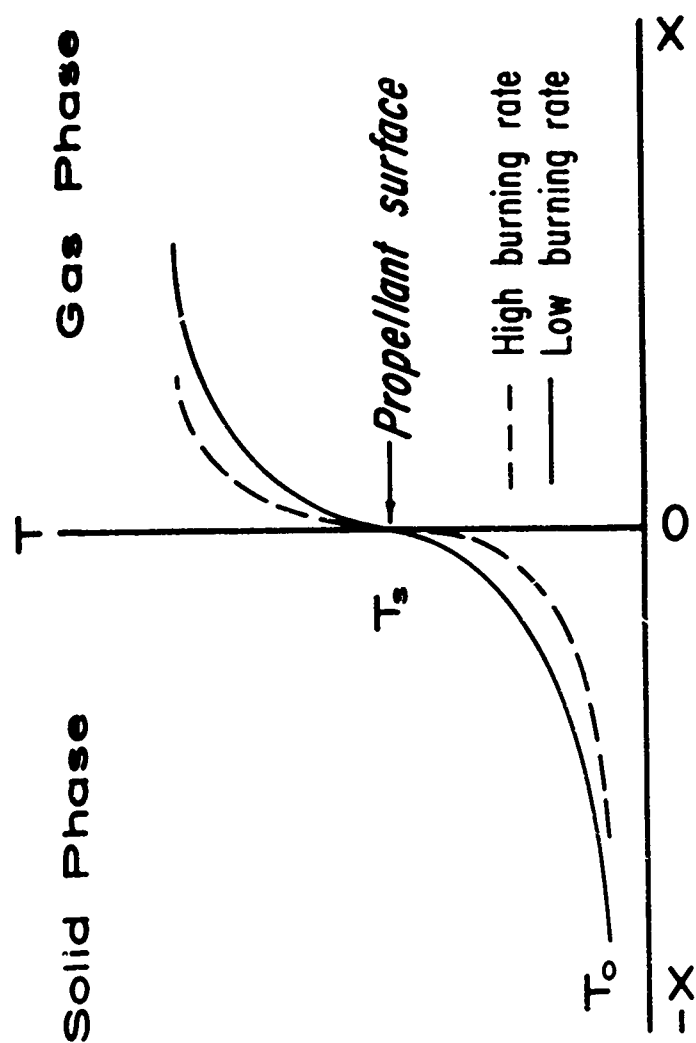


Figure 2 TEMPERATURE PROFILE IN SOLID PROPELLANT

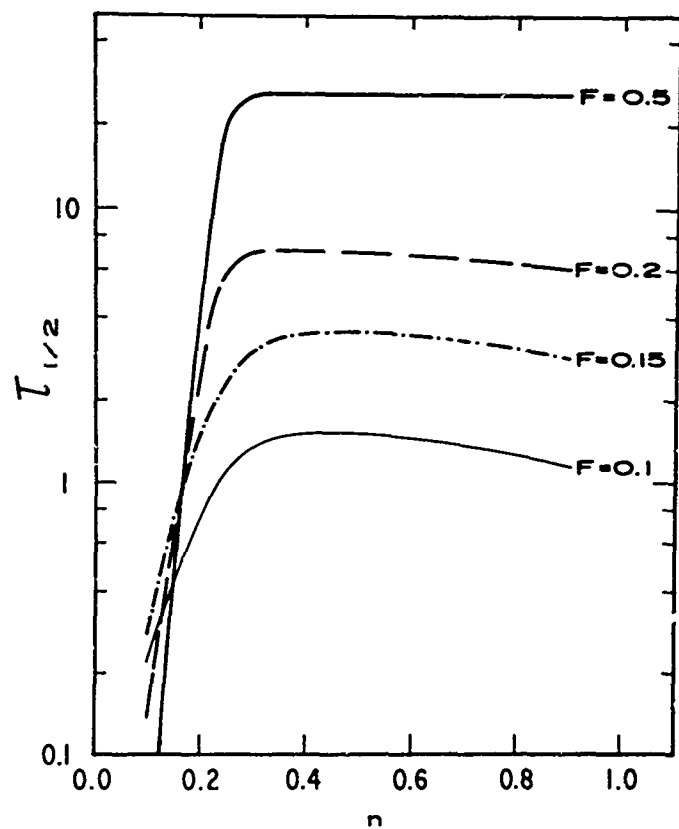


Figure 3 THE MAXIMUM DIMENSIONLESS TIME IN WHICH THE CHAMBER PRESSURE CAN EXPONENTIALLY DECAY TO HALF THE VALUE AND STILL THEORETICALLY CAUSE THE PROPELLANT COMBUSTION TO EXTINGUISH FOR AN AMBIENT PRESSURE OF ZERO.

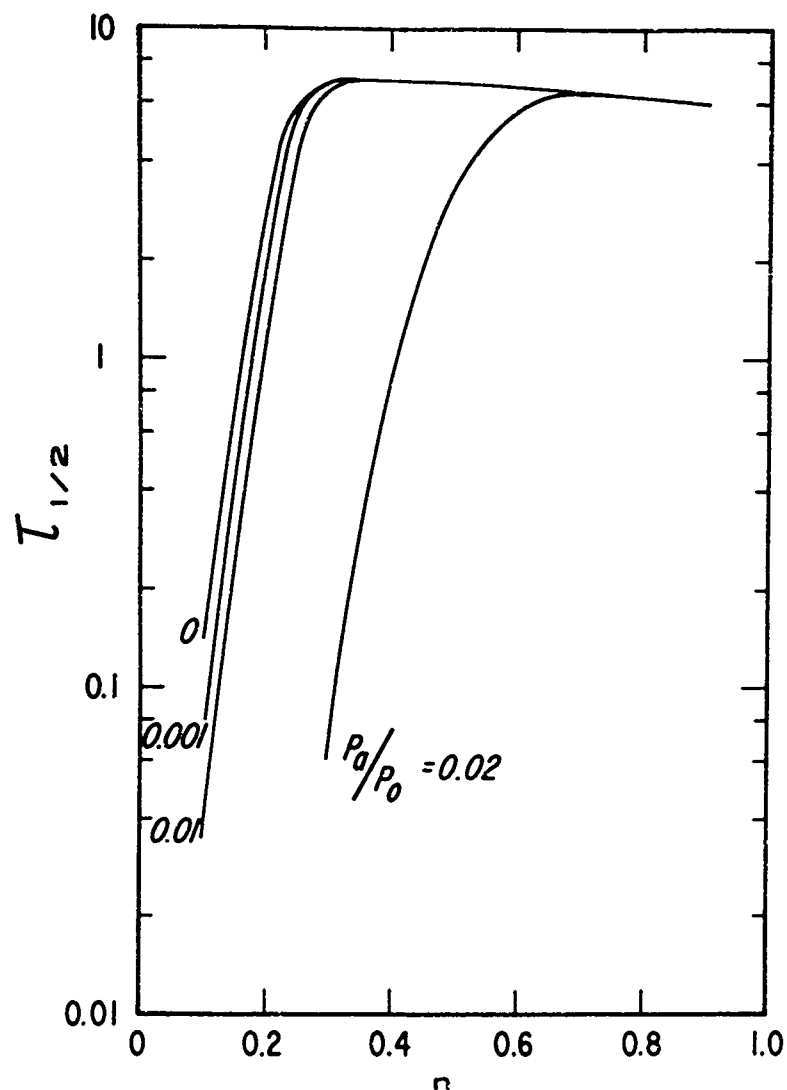


Figure 4 THE MAXIMUM DIMENSIONLESS TIME IN WHICH THE CHAMBER PRESSURE CAN EXPONENTIALLY DECAY TO HALF THE INITIAL VALUE AND STILL THEORETICALLY CAUSE THE PROPELLANT COMBUSTION TO EXTINGUISH FOR AN F VALUE OF 0.2.

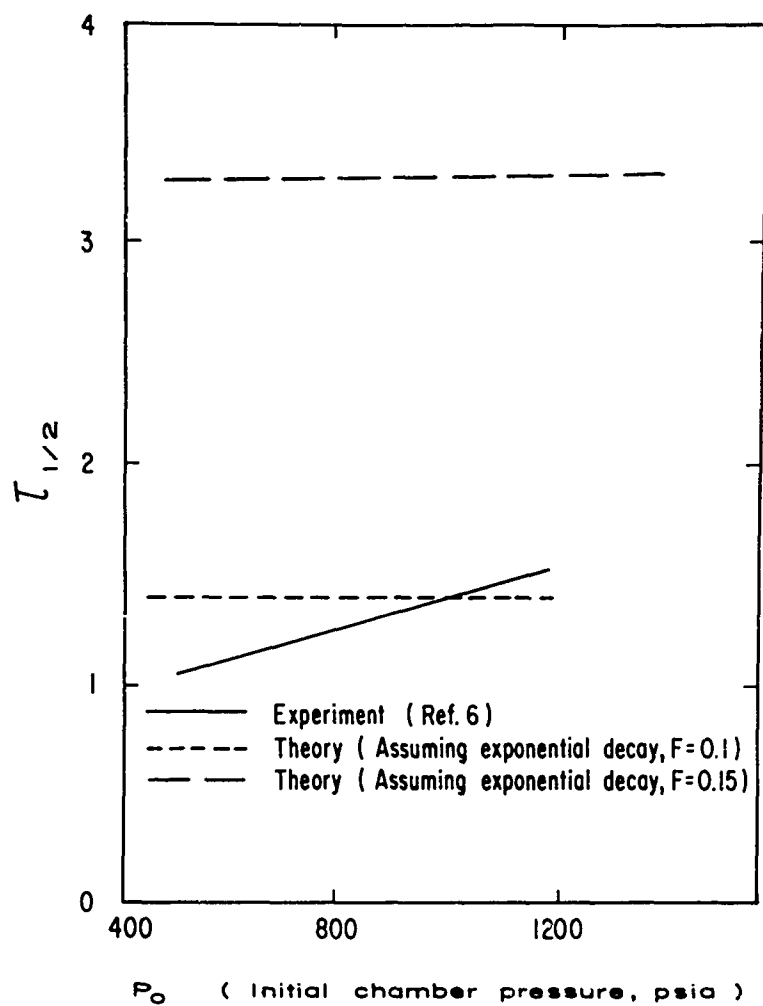


Figure 5 THE MAXIMUM DIMENSIONLESS TIME IN WHICH THE CHAMBER PRESSURE CAN DECAY TO HALF THE INITIAL VALUE AND STILL EXTINGUISH THE PROPELLANT COMBUSTION.

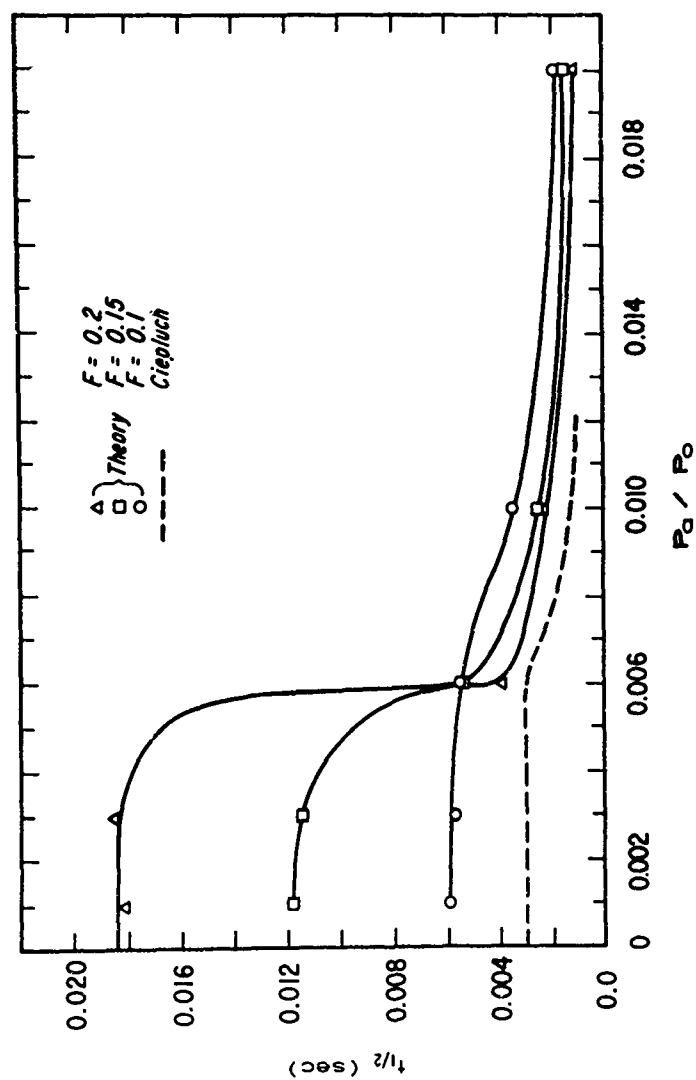


Figure 6 THE MAXIMUM TIME DURING WHICH THE CHAMBER PRESSURE CAN DECAY TO HALF THE INITIAL VALUE AND STILL EXTINGUISH THE PROPELLANT COMBUSTION. THE THEORETICAL VALUES ASSUME EXPONENTIAL PRESSURE DECAY.

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## 13. ABSTRACT

This paper presents the results of a combined theoretical and experimental study of the process in which solid propellant combustion is terminated by a rapid drop in pressure. Experimentally, propellant burning in a small rocket motor was subjected to a rapid pressure drop when an auxiliary nozzle sizes for the auxiliary nozzle and the boundary between extinction and non-extinction was determined. The results were then compared to the predictions of the theoretical model which was based on the assumption that extinction occurs when the heat absorption by the solid propellant surface exceeds the heat transfer to the solid propellant surface from the combustion gas. In general, the theoretical predictions agreed well with both the experimental results gathered in the program and those published by other investigators.

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| KEY WORDS                   | LINK A |    | LINK B |    | LINK C |    |
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|                             | ROLE   | WT | ROLE   | WT | ROLE   | WT |
| Propellant Extinction       |        |    |        |    |        |    |
| Solid Propellant Combustion |        |    |        |    |        |    |
| Transient Combustion        |        |    |        |    |        |    |

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